Single-Event Effect Radiation Test Results of Radiation-Hardened IEEE1394 Firewire ASICs

Bruce E. Pritchard, *Member, IEEE*, Joe B. Underwood, W. Doug Murlin, Andrea M. Coleman, Kenneth D. Wolfram, *Member*, *IEEE*, Jeff B. Warner, and Craig C. Hafer

Abstract **- This paper presents single-event radiation test results for two Aeroflex IEEE1394 FireWire ASICs developed by the NPOESS Integrated Program Office. Both ASICs performed very well and met all NPOESS radiation requirements for space usage.**

Keywords **- Firewire, 1394, APHY, LLC, latchup, single-event upset, NPOESS, IPO**

I. INTRODUCTION

THIS paper documents single-event effects (SEE) radiation test results on two IEEE1394 Firewire ASICs made by Aeroflex Colorado Springs. This work was funded by the Integrated Program Office (IPO) for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) next-generation weather satellite constellation. The IPO is a joint agency comprised of the National Oceanographic and Atmospheric Administration (NOAA), which is part of the Department of Commerce (DoC), the Department of Defense (DoD), and the National Aeronautics and Space Agency (NASA).

The IPO undertook development of a high-speed, fault-tolerant, radiation-hardened data bus because the data rates of the sensor complement selected for the NPOESS satellite system greatly exceeded the technological capabilities at the time (e.g., 1553). A survey (circa 2000) indicated that only two options, “FireWire” and “SpaceWire,” were viable, and both were in their infancy. Firewire, or IEEE-1394, was selected based on its capability and flexibility. Other commercially available 1394 ASICs have been tested previously [1], but they were found to be unsuitable for most space applications. Thus, a harder set of 1394 ASICs was designed using hardening techniques established by Aeroflex and ATK/Mission Research, consisting of epitaxial starting material and hardened cell designs.

The implementation consists of three separate ASICs: the Link-Layer Controller (LLC), the Digital Physical Layer (DPHY), and the Analog Physical Layer (APHY). The LLC handles the link-layer functions of the protocol, interfacing to the cPCI backplane and the physical layer. The DPHY handles all the digital functions of the physical layer, transferring data between the LLC and the APHY. The APHY incorporates all analog functions to transfer 1394 packets onto the cable, reconstructs the clock signal, and interprets status and arbitration.

Two of these ASICs were tested by Northrop Grumman in February 2004 to establish their level of susceptibility to single-event effects to evaluate their applicability for the NPOESS program. The tested ASICs included an APHY chip designed by ATK/Mission Research using the MRC cell library and fabricated at an AMI foundry on a 0.6-µm CMOS process, and the LLC chip, which was designed by Aeronix (who also designed the DPHY) using the Aeroflex cell library and fabricated at the TSMC foundry using a 0.25-µm CMOS process. This paper briefly describes the hardening techniques used, and then focuses on the SEE radiation testing approach, the test results, and the results of the analysis on the test data. Table I provides an overview of the ASIC characteristics.

TABLE I. SUMMARY OF AEROFLEX 1394 ASIC CHARACTERISTICS

	APHY	LLC
Voltage (nom.)	5.0 V	3.3 V (I/O), 2.5 V (core)
Foundry	AMI	TSMC
Process	0.6 µm on epi	0.25 µm on epi
Bits	Receivers: 29 F/Fs per port; Transmitters: 7 F/Fs per port (3 receiver ports & 3 transmitter ports)	Scan-chain = 8,956 F/Fs; MEMBIST: 8,192 bits + 200 F/Fs for BIST logic
Cell Library	Custom (MRC)	Aeroflex

Manuscript received July 19, 2004. The work in this paper was funded by the NPOESS Integrated Program Office (IPO), and was performed at Northrop Grumman Space Technology under IPO Contract F04701-01-C-0510.

Bruce Pritchard is with Northrop Grumman Space Technology, Redondo Beach, CA 90278 USA (e-mail: bruce.pritchard@ngc.com or bepritchard@ieee.org; telephone: 310-813-4569)

Joe Underwood is with Volt Technical Services supporting Northrop Grumman Space Technology, Redondo Beach, CA 90278 USA (joe.underwood@ngc.com, 310-812-1334).

Doug Murlin is with Northrop Grumman Space Technology, Redondo Beach, CA 90278 USA (doug.murlin@ngc.com 310-813-9196).

Andrea Coleman is with Northrop Grumman Space Technology, Redondo Beach, CA 90278 USA (andrea.coleman@ngc.com, 310-814-2393).

Ken Wolfram is with US Navy and is assigned to the NPOESS Integrated Program Office (IPO) (Ken.Wolfram@noaa.gov and Kenneth.Wolfram@nrl.navy.mil, 301-713-4769).

Jeff Warner is with Northrop Grumman Space Technology, Redondo Beach, CA 90278 USA (jeff.warner@ngc.com, 310-812-9378

Craig Hafer is with Aeroflex Colorado Springs, Colorado Springs, CO 80907 USA (craig.hafer@aeroflex.com, 719-594-8319).

II. DISCUSSION

A. Background

Aeroflex and ATK/Mission Research use a variety of hardening techniques to address the various natural space radiation environments. Epitaxial starting material is used to preclude latchup, which is a very serious problem in space for most CMOS parts. Single-event upset (SEU) in logic is typically mitigated by using redundant elements in the cell designs. Total ionizing dose is mitigated primarily by layout rules to prevent field-oxide effects, since the transistor gate oxides are now so thin that no other hardening is necessary to reach 100 krads(Si) hardness capability.

B. Test Objectives

The objectives of the testing conducted in this effort were primarily to validate the SEE hardness predictions provided by Aeroflex. (The total ionizing dose capability of the ASICs is >100 krads [2].) The reasons for performing such validations are that: (1) the APHY ASIC contains analog elements that have never been subjected to any SEE testing, and (2) the LLC uses LDFF flip-flops for logic, which had been characterized [3], but only LDL latches for memory, and these had not been characterized. A third reason was that the very design of these 1394 ASICs makes SEU testing and characterization very difficult. Thus, the principal focus of the tests was on ensuring that there was no latchup, and indeed, no latchups were observed in any of the testing. SEU data was also collected, but it was uncertain prior to testing that good quantitative SEU data could be obtained. The reasons for this are explained in the next section. Testing was also designed to note any occurrence of single-event functional interrupt (SEFI). However, none was ever observed in testing.

C. Analytical Objectives

The analytical objectives were to establish a bound for potential latchup, if observed, and also to predict bit-error rates in both the NPOESS orbit (828 km, 98.75°) as well as a geosynchronous orbit. It was not known prior to testing whether enough SEU data could be obtained to make a confident estimate of the SEU rates for the ASICs. When sufficient data is available, Weibull curve fitting is often performed. However, if there is insufficient data, a Weibull curve cannot be relied upon, especially for LET values outside the test range, because the Weibull function has no physical basis. This is especially important if it is not possible to determine a threshold LET. Therefore, the Edmonds method [4] was used to fit the SEU data, because unlike the Weibull function, the Edmonds model has a physical basis. CREME96 [5] was used to calculate all error rates.

D. Test Approach

All latchup testing was performed at high temperature and maximum specified voltage. The temperature was chosen to be slightly lower than the specified +125°C in order to accommodate the tolerance of the heaters and also to account for device self-heating due to operation in a variety of modes. Thus, the heater temperature was selected to be +110°C, as this is higher than the maximum temperature allowed in the system design requirements.

All upset testing was performed at ambient room temperature and at minimum specified device voltage.

The ASICs were tested at the Texas A&M University (TAMU) Superconducting Cyclotron. This facility was specifically chosen for the high ion energies available, which are necessary to fully penetrate the active charge-collection region of an integrated circuit (~50 microns). In addition, the overlayers of SiO_2 and aluminum (on the order of 10 microns) must also be penetrated by the ions. Thus, in order to demonstrate latchup immunity, high energy ions are required.

Four samples of each ASIC type were tested with heavy ions. For the APHY, two of the samples were operated as transmitters, and the other two were operated as receivers. No proton testing was performed on either ASIC.

III. TEST RESULTS

A. Overview of Test Results

None of the tested ASICs exhibited latchup at +110°C and worst-case voltage up to an effective LET of >110 MeV-cm^2/mg. (The requirement was to have no latchup for any LET up to 75 MeV-cm^2/mg. Thus, the performance was well above the requirement.) Maximum ion LET was 88 MeV-cm^2/mg (obtained at normal incidence). At the maximum tested angle of 45°, the effective LET (LET_{eff}) was >110 MeV-cm^2/mg. The SEU results were also quite good, with the highest rate of 4.0 x 10^{-9} errors/bit-day found for the LDL latches used in the LLC for memory in the NPOESS orbit, and all other APHY and LLC cell error rates even lower (1.4 x 10^{-10} to 7.3 x 10^{-10} errors/bit-day in the NPOESS orbit). These values are all well under the required rate of 10^{-7} errors/bit-day. No SEFI was observed for either ASIC in any of the testing. Thus, these ASICs meet the NPOESS single-event effects (SEE) radiation requirements.

B. Latchup Test Results

The first priority was to test for single-event latchup (SEL) susceptibility of the APHY and LLC ASICs. Each APHY (two connected as receivers and two connected as transmitters) and LLC was tested for SEL with gold ions having a linear energy transfer (LET) of >87 MeV-cm^2/mg(Si). When the part is tilted to an angle of 45° from the beam, the effective linear energy transfer (LET_{eff}) >110 MeV-cm^2/mg. (The beam diameter at TAMU is one inch in air, which was the case for these tests.) Neither the APHY nor the LLC ASICs exhibited any latchup at room temperature or at +110°C with maximum bias voltage(s) for LET_{eff} up to 110 MeV-cm^2/mg at a total tested (effective) fluence of 3 x 10^7 ions/cm^2.

In May 2004, Aeroflex performed additional latchup testing of the LLC (which they refer to as the WG01B) at a higher temperature than Northrop Grumman (125°C versus 110°C) at TAMU [6]. Their testing showed no latchup at

125°C with core voltage at 2.75 V and I/O voltage at 3.6 V (worst-case conditions) at LET_{eff} = 110 MeV-cm^2/mg and an effective fluence of 1 x 10^7 ions/cm^2. These were obtained with xenon ions with LET = 58.2 MeV-cm^2/mg at an angle of 58°. (Both the LET and fluence are adjusted for the angle.)

C. *Upset Test Results*

The Aeroflex APHY and LLC ASICs were tested for SEUs following completion of SEL testing. For SEU testing, the parts were operated at ambient room temperature and at minimum device voltage(s) (worst case for SEU). The APHY receiver was tested for SEU at LET_{eff} values between 30 and 155 MeV-cm^2/mg, and the APHY transmitter was tested for SEU at values between 54 and 125 MeV-cm^2/mg. The APHY transmitter was not tested below LET = 54 MeV-cm^2/ mg, because only two bit errors were observed during a total fluence of 6 x 10^7 ions/cm^2.

The LLC ASIC was tested for SEU in two modes: (1) three separate scan-chains (7077 F/F, 1521 F/F, and 358 F/F) tested between LET = 30 to 138 MeV-cm^2/mg; and (2) MEMBIST (Memory Built-In Self Test), tested at LET = 54 and 85 MeV-cm^2/mg at two different flux rates (see next section) to determine whether multiple SEUs were occurring during the higher flux counting-window time period. The threshold for SEU onset is approximately LET = 16 MeV-cm^2/mg in the LLC ASIC and approximately LET = 19 MeV-cm^2/mg in the APHY ASIC.

IV. Data Analysis

A. *LLC SEU Data Analysis*

Fig. 1 shows the LLC scan-chain data and the fit for SEU cross section logarithms versus reciprocal LET, as developed in diffusion analysis by Edmonds [4]. The chart sums all three scan-chains together for a total of 8,956 flip-flops. (Edmonds uses natural logarithms of cross sections in square microns per bit.) The variance interpretation level for the LLC data points of >98% is excellent. The correlation coefficient is the square root of the variance interpretation and is greater than 99% for the LLC. This agrees with a visual inspection, which shows a very good fit with the data points.

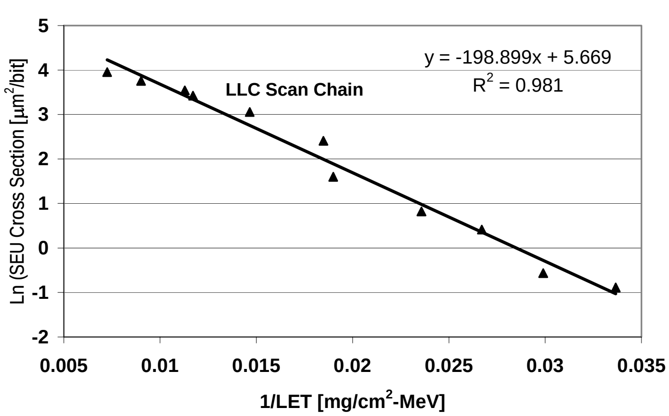

Fig. 1. SEU Cross Section Logarithms vs. 1/LET for LLC Scan Chain.

Fig. 2 shows averaged SEU scan-chain cross sections for the LLC chip versus LET and the Edmonds fit mapped into this graph. Extrapolation gives an estimated threshold of ~16 MeV-cm²/mg, and the apparent saturation cross section is approximately 6.7 x 10^{-7} cm^2/bit. While Edmonds cautions against extrapolation to low LET values, the value of 16 is close to the estimate of 14.5 MeV-cm²/mg provided by Aeroflex [3].

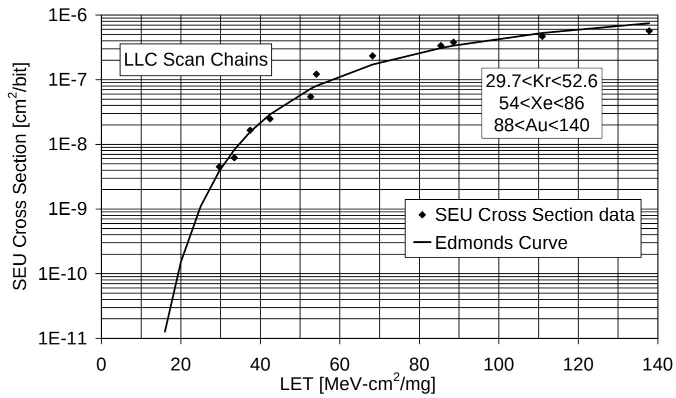

Fig. 2. SEU Cross Section vs. LET for LLC Scan Chain (Edmonds Fit).

Fig. 3 shows the data points for the SEU cross-section logarithms versus 1/LET for the LLC MEMBIST for both high- and low-flux rates. The MEMBIST tests 8,192 bits, plus approximately 200 flip-flops. The data shows little difference in measured cross section between the two different flux rates, which are about a factor of seven apart. (The rates are 1.2 x 10^5 and 1.7 x 10^4 ions/cm^2-sec, respectively, at LET = 85 MeV-cm²/mg and 1.8 x 10^5 and 2.6 x 10^4 ions/cm^2-sec at 54 MeV-cm²/mg. In each case, the higher flux is about seven times greater than the lower flux.)

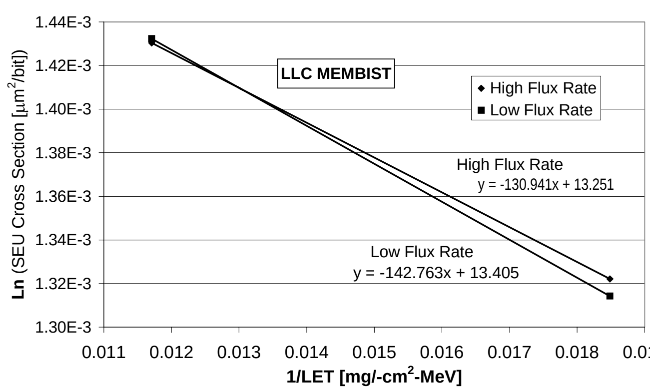

Fig. 3. SEU Cross Section Logarithms vs. 1/LET for LLC MEMBIST.

Fig. 4 shows the same SEU cross-section data for the LLC MEMBIST chart at high- and low-flux levels to be fairly close, indicating that the SEU counting instrumentation does not appear to be missing SEUs due to high flux rates used during the scan-chain testing. The two Edmonds curves were based on averaged high- and low-flux rate data. Because these curves were only based on data at the two tested LET levels, the extrapolations down to threshold are obviously tentative. However, extrapolations with a Weibull curves would be impossible, as there would be an infinite number of curves that could pass through the two pairs of data points. Since the Edmonds model has a physical basis, an extrapolation of limited confidence can be made. The two extrapolated thresholds of 12 and 13 MeV-cm²/mg, respectively, for the high- and low-flux cases, could change considerably if more data were available at lower LET values. The extrapolated thresholds are slightly below the value provided by Aeroflex for the LDFF flip-flop (14.5 MeV-cm²/mg), but the extrapolation cannot be considered very accurate without additional data at lower LET values. The saturation cross section appears to be no more than about 2.4 x 10^{-7} cm^2/bit in either case.

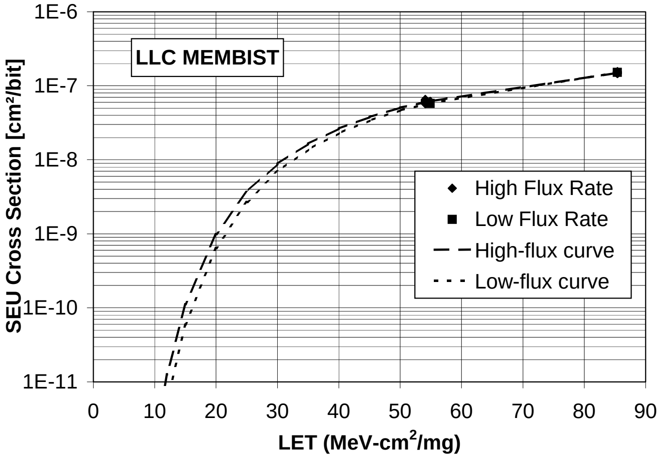

Fig. 4. SEU Cross Section vs. LET for LLC MEMBIST for High- and Low-Flux Data (Edmonds Model).

B. APHY SEU Data Analysis

Fig. 5 shows the APHY Receiver SEU logarithmic cross section versus reciprocal LET. The Edmonds fit variance interpretation value of 0.9847 also results in a correlation coefficient greater than 99%.

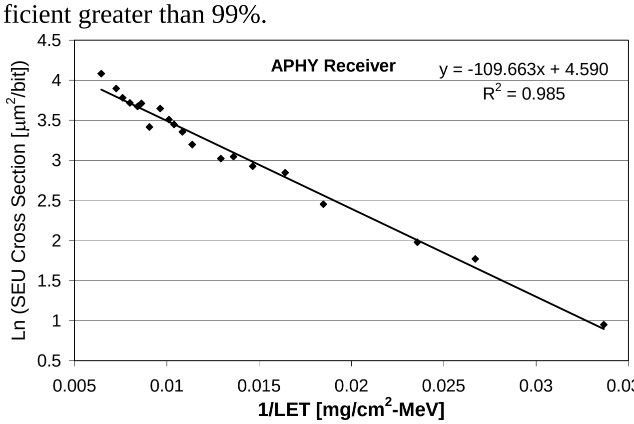

Fig. 5. SEU Cross Section Logarithms vs. 1/LET for APHY Receiver.

Fig. 6 shows the APHY Receiver SEU cross section data versus LET, the derived Edmonds fit, and an extrapolation of the Edmonds curve. The high correlation coefficient indicates the APHY receiver LET threshold is probably very close to the indicated 19 MeV-cm^2/mg, and the apparent saturation cross section is approximately no more than 6.9 x 10^{-7} cm^2/ bit.

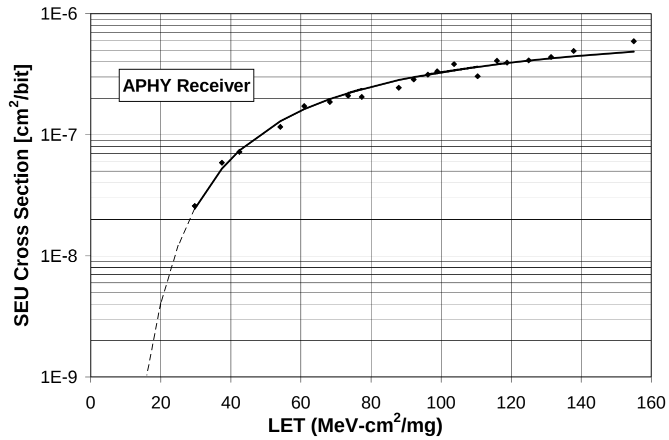

Fig. 6. SEU Cross Section vs. LET for APHY Receiver (Edmonds Fit).

Fig. 7 shows the SEU cross section logarithms for the APHY transmitter as a function of reciprocal LET. The Edmonds fit variance interpretation value of 0.9642 results in a correlation coefficient >98%.

The APHY transmitter's lower variation interpretation level shown in Fig. 7 may be due to a much lower SEU cross section rate for the transmitter than observed in the APHY receiver. The maximum number of SEUs observed during the APHY transmitter test in a single run was only eight.

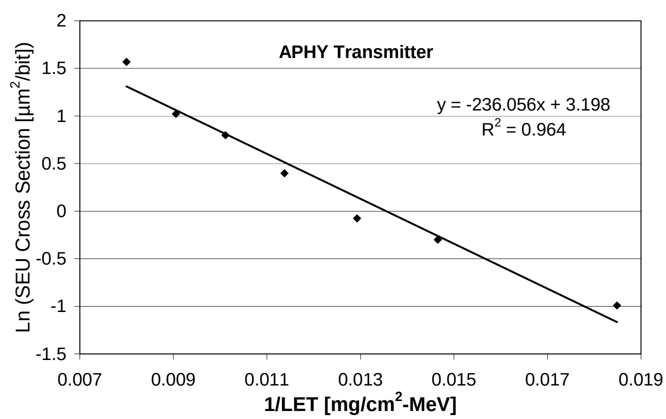

Fig. 7. APHY Transmitter SEU Cross Section Logarithms vs. 1/LET.

Fig. 8 shows the APHY transmitter SEU cross section data versus LET, the Edmonds fit curve with an extrapolation to a threshold. The Edmonds theoretical model does an excellent job in matching all SEU cross section data at high LET and also fits oblique-incidence SEU cross section data within experimental error. The APHY transmitter LET threshold is probably very close to the indicated 19 MeV-cm^2/mg, and the apparent saturation cross section is no more than about 4.4 x 10^{-8} cm^2/bit.

Each port of the APHY receiver has 29 F/Fs, and each port of the transmitter has nine F/Fs. There are three receiver ports and three transmitter ports in each ASIC. Only one port of each APHY ASIC was tested.

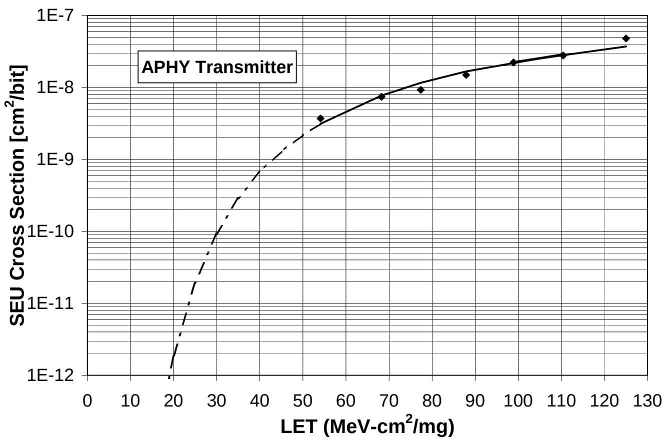

Fig. 8. APHY Transmitter SEU Cross Section vs. LET (Edmonds Fit).

V. Summary

This paper provides heavy ion radiation test results for two radiation-hardened IEEE 1394 Firewire ASICs made by Aeroflex for the NPOESS Integrated Program Office. Northrop Grumman Space Technology tested the APHY and LLC ASICs made by Aeroflex at the Texas A&M University (TAMU) Superconducting Cyclotron. The APHY and LLC ASICs showed no latchup at worst-case temperature and voltage conditions up to an effective LET of >110 MeV-cm^2/mg. This easily exceeded the requirement that no latchup occur for any LET up to 75 MeV-cm^2/ mg.

Table II summarizes the heavy-ion test results and the estimated error rates for the two tested Aeroflex ASICs. The LLC has 8,956 F/Fs in the three scan chains, while the MEMBIST has 8,192 latches and about 200 F/Fs in BIST logic. This design difference may explain why the MEMBIST SEU rate is 8 times higher than the scan-chain SEU rate. The differences in the SEU cross sections for each scan chain were not statistically significant. The higher APHY receiver SEU rate (five times higher than the APHY transmitter SEU rate) may be due to single-event transients in receiver arbitration comparators that are manifested as SEUs in the receiver circuit.

Overall, the SEU results were quite good. The LLC had an error rate of 1.7 x 10^{-8} errors/bit-day for the LDL latches used in the memory for the quiet, geosynchronous orbit, which is only 2.5 times higher than the value calculated by Aeroflex [3] for the LDFF cell (i.e., 6.74 x 10^{-9} errors/bit-day). This is not unexpected, since the LDL is a latch rather than a full flip-flop. For NPOESS, these tests indicate an error rate of 4.0 x 10^{-9} errors/bit-day for the LLC memory bits in the NPOESS orbit. All other APHY and LLC cell error rates were even lower, ranging from 6 x 10^{-10} to 3.1 x 10^{-9} errors/bit-day in the quiet, geosynchronous orbit, and 1.4 x 10^{-10} to 7.3 x 10^{-10} errors/bit-day in the NPOESS orbit. These values are all well under the required rates of 10^{-7} errors/bit-day in the quiet, geosynchronous orbit (<2.5 x 10^{-8} in the NPOESS orbit). Calculated SEU rates for GEO are in reasonable agreement.

Differences are attributed to lack of data at LET values lower than 30 in our testing, as well as use of different software to analyze data and predict SEU rates. (Aeroflex uses SpaceRadiation 4.0, whereas Northrop Grumman uses CREME96.) With regard to operation during peak solar event fluxes, NPOESS equipment is only required to survive, but is not required to operate within specifications.

Thus, the tested APHY and LLC ASICs made by Aeroflex meet the SEE radiation requirements for NPOESS, and they are also expected to perform well in a quiet, geosynchronous orbit.

VI. Acknowledgments

The authors wish to acknowledge the support provided by Jim M. Nelson, Paul MacFalda, Marlon Marquez, Khanh Thai, and Howard Spitzer of Northrop Grumman Space Technology, and Donna Hathaway, Peter Milliken, and Susan Meadows of Aeroflex Colorado Springs.

This project was funded under IPO Contract F04701-01-C-0510.

VII. References

[1] C. Seidleck, S. Buchner, H. Kim, P.W. Marshall, and K. LaBel, "Test Methodology for Characterizing the SEE Response of a Commercial IEEE 1394 Serial Bus (FireWire)," *IEEE Trans. Nuc. Sci.*, Dec. 2002, pp.3129-3134.

[2] Aeroflex test report "NPOESS LLC ASIC, WG01A, Logic Test Chip, Total Dose Radiation Step Stress AC Characterization," Jan. 23, 2004.

[3] C. Hafer, "Single Event Effects Results of the Aeroflex NX02 0.25μm Test Chip," Aeroflex Colorado Springs (revised Aug. 19, 2003; original by J.M. Benedetto, MRC, June 2003).

[4] L.D. Edmonds, "SEU Cross Sections Derived from a Diffusion Analysis," *IEEE Trans. Nuc. Sci.*, Dec. 1996, pp. 3207-3217.

[5] A.J. Tylka, James H. Adams, Jr., P.R. Boberg, B. Brownstein, W.F. Dietrich, E.O. Flueckiger, E.L. Petersen, M.A. Shea, D.F. Smart, and E.C. Smith, "CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code," *IEEE Trans. Nuc. Sci.*, Dec. 1997, pp. 2150-2160.

[6] C. Hafer, "Single Event Latch-up Summary for the WG01B," Aeroflex Colorado Springs, received June 10, 2004.

Table II. Summary of Heavy Ion Test Results and Estimated Error Rates for Aeroflex 1394 ASICs

ASIC Test Mode	LET_{th} [MeV-cm^2/mg]	Cross Section [cm^2/bit]	GEO SEU rate [errors/bit-day]	NPOESS SEU rate [errors/bit-day]
APHY/Transmitter	19	4.4 x 10^{-8}	6.0 x 10^{-10}	1.4 x 10^{-10}
APHY/Receiver	19	6.9 x 10^{-7}	3.1 x 10^{-9}	7.3 x 10^{-10}
LLC/Scan-Chain	16	6.7 x 10^{-7}	2.1 x 10^{-9}	4.9 x 10^{-10}

LLC/MEMBIST	~13	2.4×10^{-7}	1.7×10^{-8}	4.0×10^{-9}
LDFF (in TSMC HGZ1 test chip)	14.5	2.8×10^{-7}	6.74×10^{-9}	1.6×10^{-9} (est'd.)